TM No. 851080

NAVAL UNDERWATER SYSTEMS CENTER
NEW LONDON LABORATORY
NEW LONDON, CONNECTICUT 06320

Technical Memorandum

HYDRODYNAMIC NOISE AND SURFACE COMPLIANCE--
AN OVERVIEW OF THE NAVAL UNDERWATER SYSTEMS CENTER
IR/IED PROGRAM

DATE: 15 May 1985

Prepared by:

DR. HENRY BAKEWELL, JR.
Towed Array R&D Branch
Code 3232

DR. WILLIAM A. VON WINKLE
Associate Technical
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FOREWORD

This paper was prepared as an invited paper for presentation at the 109th Meeting of the Acoustical Society of America at Austin, Texas, 8-12 April 1985 in the session on Underwater Flow Noise. An overview is presented of the Naval Underwater Systems Center's Independent Research and Exploratory Development Program on Hydrodynamic Noise on Compliant Surfaces. Three specific efforts are discussed; an experimental investigation, an analytical modeling effort and a numerical modeling study.

ADMINISTRATIVE INFORMATION

This technical memorandum was prepared under NUSC IR Project No. A70201, "Flow Noise Reduction for Mobile Acoustic Sensors", Principal Investigator H. P. Bakewell, Jr. (Code 3232). The sponsoring activity is NAVMAT 05B (CAPT Z. L. Newcomb).

THE OBJECTIVE OF THE NAVAL UNDERWATER SYSTEMS CENTER INDEPENDENT RESEARCH AND EXPLORATORY DEVELOPMENT PROGRAM ON COMPLIANT SURFACES IS STATED IN THIS SLIDE. SPECIFICALLY, WE ARE INVESTIGATING TURBULENT FLOWS OVER COMPLIANT LAYERS TO DETERMINE WHETHER A CLASS OR CLASSES OF SUCH LAYERS CAN BE DEVISED FOR CONTROL AND REDUCTION OF HYDRODYNAMIC NOISE. TO ACCOMPLISH THIS END WE ARE ADDRESSING THE COUPLED FLUID/ELASTIC PROBLEM TO CHARACTERIZE THE FLOW/LAYER INTERACTIONS, RESULTANT EFFECTS ON THE TURBULENT VELOCITY COMPONENTS AND EFFECTS BOTH AT THE SURFACE AND WITHIN THE LAYER.

THE MOTIVATION FOR THE NUSC PROGRAM IS PROVIDED BY AN EXPERIMENT IN 1960 IN WHICH SIGNIFICANT REDUCTIONS IN THE TURBULENT BOUNDARY LAYER WALL PRESSURE SPECTRA WERE MEASURED ON A VEHICLE COATED WITH U.S. RUBBER "LAMIFLO". THE "LAMIFLO" COATING WAS BASICALLY A VERSION OF A "DOLPHIN-LIKE" SURFACE DEVISED TO EXTEND KRAMER'S WELL KNOWN DRAG REDUCTION INVESTIGATIONS INTO THE FLOW NOISE DOMAIN. THE MEASURED FLOW NOISE REDUCTIONS HAVE YET TO BE ADEQUATELY EXPLAINED OR UNDERSTOOD. THUS, SIMILAR TO RECENT ONR EFFORTS TO REVISIT THE ISSUE OF DRAG REDUCTION AND COMPLIANT SURFACES, THE NUSC PROGRAM SEEKS TO DEVELOP AN ADEQUATE PHYSICAL FRAMEWORK WITHIN WHICH THE EFFECTS OF COMPLIANT LAYERS ON FLOW NOISE MAY BE UNDERSTOOD. NOTE THAT OUR CURRENT EFFORTS ARE FOCUSED ON PASSIVE LAYERS WITH CONSIDERATION OF ACTIVE LAYERS AS A POSSIBLE PROGRAM EXPANSION AREA AT SOME LATER DATE.

NEXT SLIDE.

THIS SLIDE DEPICTS THE EXPERIMENTAL SETUP FOR THE 1960 INVESTIGATION OF FLOW NOISE REDUCTION ON COMPLIANT SURFACES. THE UPPER LEFT HAND PORTION OF THE FIGURE "A" ILLUSTRATES THE DETAILS OF THE COATING. BASICALLY THE COATING WAS A SANDWICH OF TWO LAYERS OF RUBBER SEPARATED BY REGULARLY SPACED RUBBER PEDESTALS. THE RESULTANT VOIDS BETWEEN THE TWO LAYERS COULD BE FILLED WITH A FLUID OF CHOICE.

THE BOTTOM LEFT PORTION OF THE FIGURE "B" ILLUSTRATES THE THREE FOOT LONG TEST VEHICLE AND THE PRESSURE COEFFICIENT FOR THE VEHICLE. THE NUMERALS ONE TO FOUR INDICATE THE LOCATIONS OF THE FLUSH MOUNTED HYDROPHONES WHICH HAD A DIAMETER OF APPROXIMATELY 1/8 OF AN INCH. TWO VEHICLES WERE TESTED; AN UNCOATED CONTROL BODY AND A COATED TEST BODY. ON THE COATED BODY THE HYDROPHONES EXTENDED THROUGH THE COATING SUCH THAT THE HYDROPHONE FACE WAS FLUSH WITH THE EXTERIOR OF THE COMPLIANT LAYER.

THE RIGHT SIDE OF THE FIGURE "C" SHOWS THE TEST GEOMETRY. DURING EACH TEST THE VEHICLE WAS ALLOWED TO FREE FALL OVER A DISTANCE OF 85 FEET. ELECTRICAL SIGNALS FROM THE HYDROPHONES WERE PROVIDED BY THE TRAILING WIRE WHICH WAS DEPLOYED OVER A PULLEY TO GIVE VEHICLE VELOCITY DATA. THE WATER TEMPERATURE IN THE TANK WAS 93^{o}F WHICH MAY HAVE CORRESPONDED TO A PARTICULARLY OPTIMUM REGION FOR THE ELASTIC PROPERTIES OF THE COATING MATERIAL UNDER TEST.

NEXT SLIDE.

TYPICAL WALL PRESSURE SPECTRA MEASURED DURING THE 1960 EXPERIMENT ARE SHOWN IN THIS SLIDE. THE ORDINATE IS GIVEN IN DECIBELS REFERENCE $(1 \mu Pa)^2$. THE FREQUENCY RANGE OF THE DATA EXTENDED FROM 200 Hz TO 10 kHz. THE DASHED CURVE IN THE UPPER PORTION OF THE FIGURE IS THE TBL WALL PRESSURE SPECTRUM OBTAINED WITH HYDROPHONE 2 ON THE UNCOATED CONTROL VEHICLE. THE SOLID CURVE IS THE WALL PRESSURE SPECTRUM MEASURED WITH HYDROPHONE 2 ON THE COATED VEHICLE WHEN THE INTERNAL VOIDS IN THE COATING WERE FILLED WITH AIR.

THE LOWER CURVE SHOWN AS A BROKEN LINE IS THE TBL WALL PRESSURE SPECTRUM MEASURED BY HYDROPHONE 2 ON THE COATED VEHICLE WHEN THE INTERNAL SPACE IN THE COATING WAS FILLED WITH WATER. IN THIS CASE A MAJOR REDUCTION IN THE MEASURED WALL PRESSURE IS OBSERVED OVER THE ENTIRE FREQUENCY RANGE WITH MAXIMUM EFFECTS EVIDENT AT MID FREQUENCIES.

THESE RESULTS, WHILE REMARKABLE, PROVIDE LITTLE INSIGHT INTO THE PHYSICS OF THE SITUATION. THE SPECTRAL LEVELS MEASURED BY THE SMALL HYDROPHONES ARE AN INTEGRAL OVER ALL WAVENUMBERS AND ARE PRESUMABLY DOMINATED BY EFFECTS AT CONVECTIVE WAVENUMBERS. A COMPLETE EXPLANATION OF THE EFFECTS OF A COMPLIANT SURFACE REQUIRES SPECTRAL INFORMATION AS A FUNCTION OF BOTH FREQUENCY AND WAVENUMBER AS WELL AS ADDITIONAL SUPPORTING DETAILS ON AND WITHIN THE LAYER AND IN THE FLOW.

NEXT SLIDE.

IN THIS SLIDE WE HAVE CHRONOLOGICALLY IDENTIFIED EFFORTS IN COMPLIANT LAYER TECHNOLOGY FOR NOISE REDUCTION. THE INITIAL WORK AT NUSL IN 1960 WAS JUST DESCRIBED. A SUBSEQUENT EXPERIMENTAL EFFORT PRODUCED A VARIED SET OF RESULTS, LARGELY INCONCLUSIVE. A POSSIBLE REASON FOR THE INCONCLUSIVENESS IS SUGGESTED BY THE WIDE RANGE OF TEMPERATURE VARIATIONS DURING THESE TESTS AND CURRENT KNOWLEDGE OF THE STRONG TEMPERATURE DEPENDANCE EXHIBITED BY THE PROPERTIES OF ELASTOMERIC MATERIALS.

IN THE 1970'S SIGNIFICIANT SOVIET ACTIVITIES WERE ONGOING AS EVIDENCED BY OPEN PUBLICATIONS ON COMPLIANT MATERIAL PROPERTIES. AN EXPERIMENT WAS EVEN DESCRIBED IN WHICH A DOLPHIN WAS INSTRUMENTED WITH FLUSH PRESSURE TRANSDUCERS. HOWEVER, NO DATA WERE GIVEN. ONE OF THE LATEST EXPERIMENTS SUGGESTS SOME POSSIBLE FLOW NOISE REDUCTION.

MORE RECENTLY OUR BRITISH FRIENDS ACROSS THE ATLANTIC HAVE BEEN ACTIVELY INVOLVED IN COMPLIANT SURFACE STUDIES WHICH HAVE APPEARED IN THE JOURNAL OF FLUID MECHANICS AND THE JOURNAL OF SOUND AND VIBRATION AS WELL AS IN PRESENTATIONS TODAY AT THIS MEETING.

CONCURRENT WITH THE BRITISH EFFORT IS THE NUSC IR/IED PROGRAM WHICH IS THE SUBJECT OF THIS PAPER. THE PROGRAM CONSISTS OF THREE EFFORTS; EXPERIMENTAL, ANALYTICAL, AND NUMERICAL WITH A SUPPORTING EFFORT IN MATERIAL SCIENCE TO PROVIDE STATE-OF-THE-ART CHARACTERIZATION OF CANDIDATE LAYER MATERIAL PROPERTIES.

NEXT SLIDE.

THIS SLIDE OUTLINES OUR EXPERIMENTAL EFFORT IN COMPLIANT LAYER NOISE REDUCTION. INITIALLY EXPERIMENTS ARE BEING CONDUCTED IN THE NAVAL UNDERWATER SYSTEMS CENTER WATER TUNNEL AT NEW LONDON, CT. WHILE ONE MIGHT IMMEDIATELY RAISE QUESTIONS CONCERNING NOISE CONTAMINANTS IN A CLOSED LOOP FLOW FACILITY, SUCH ISSUES HAVE BEEN ADDRESSED. THE ADVANTAGE OF WORKING IN A LABORATORY ENVIRONMENT IS THAT EXPERIMENTS CAN BE RUN FOR LONG TIMES UNDER CONSTANT VELOCITY AND TEMPERATURE CONDITIONS. IN ADDITION THE NUMBER OF PARAMETERS UNDER INVESTIGATION VIRTUALLY DICTATES A LABORATORY EXPERIMENT AS OPPOSED TO AN EXPERIMENT UTILIZING A FREE FALLING OR BUOYANT TEST VEHICLE.

THE PARAMETERS TO BE EXPERIMENTALLY DETERMINED ARE LISTED ON THIS SLIDE. THEY INCLUDE; THE TBL FLUCTUATING WALL PRESSURE STATISTICS, THE TBL NOISE WITHIN THE LAYER, THE FLUCTUATING WALL SHEAR STRESS CHARACTERISTICS, THE TURBULENT FLUCTUATING VELOCITY CHARACTERISTICS AND THE SURFACE DISPLACEMENT OF THE COMPLIANT LAYER.

NEXT SLIDE.

THE EXPERIMENTAL SETUP IN THE NUSC/NL WATER TUNNEL IS SHOWN IN THIS SLIDE. THE TEST SECTION IS RECTANGULAR WITH A 4 INCH HEIGHT, A 12 INCH SPAN AND A STREAMWISE LENGTH OF 96 INCHES. THE EXPERIMENTS ARE BEING CONDUCTED ON THE BOTTOM PLATE IN THE TEST SECTION. AS CAN BE SEEN, THE BOTTOM TEST PLATE IS ACTUALLY A FALSE BOTTOM IN THE TUNNEL THAT WAS ORIGINALLY DESIGNED TO PERMIT VARIATION OF THE PRESSURE GRADIENT. THE OLD BOTTOM PLATE HAS BEEN REPLACED WITH A NEW PLATE CONSISTING OF REMOVABLE INSERTS TO ALLOW INSERTION OF COMPLIANT LAYER SPECIMENS FOR TEST. IN THIS MANNER COMPLIANT LAYERS OF VARYING LENGTH UP TO NEARLY THE FULL STREAMWISE LENGTH OF THE TEST SECTION CAN BE ACCOMODATED. THE COMPLIANT LAYER TEST SPECIMENS ARE FABRICATED IN STEEL TRAY-LIKE FIXTURES THAT ARE BOLTED TO THE SUPPORT RAILS FOR THE BOTTOM TEST PLATE.

NEXT SLIDE.

THIS SLIDE DESCRIBES THE MEASUREMENTS BEING UNDERTAKEN AND THE TYPES OF SENSORS BEING USED. FLUCTUATING PRESSURE MEASUREMENTS WILL BE MADE AT THE SURFACE OF THE COMPLIANT LAYER, INTERIOR TO THE LAYER AND AT THE BACKING PLATE UNDER THE LAYER. SENSORS WILL INCLUDE BOTH STANDARD FLUSH MOUNT PROBE HYDROPHONES AND END CAPPED CERAMICS AS WELL AS BULK MODE POLYMER SENSORS. THE LATTER SENSORS SHOULD PROVIDE A LESSER IMPEDANCE MISMATCH WITH THE COMPLIANT LAYER MATERIAL UNDER TEST THAN PROBES OR CERAMICS. HOWEVER, THE POLYMER SENSORS ARE NOT INSENSITIVE TO STRAIN WHICH MAY CONTAMINATE THE PRESSURE RESPONSE.

ACCELEROMETERS WILL BE USED TO DETERMINE THE MOTION OF THE BACKING PLATE SUPPORTING THE COMPLIANT LAYER. AS IN THE CASE OF THE PRESSURE SENSORS, IT IS ANTICIPATED THAT ARRAYS OF ACCELEROMETERS WILL BE USED TO CHARACTERIZE THE WAVEVECTOR FREQUENCY CONTENT OF THE ACCELERATION SPECTRA.

STANDARD HOT FILM PROBES WILL BE USED TO CHARACTERIZE THE TBL FLUCTUATING WALL SHEAR STRESS. POLYMER FILM SENSORS MAY ALSO BE INCLUDED TO PROVIDE A MEASURE OF THE SHEAR IN THE COMPLIANT LAYER IN RESPONSE TO THE FLUCTUATING TBL WALL SHEAR STRESS.

THE FLUCTUATING VELOCITY COMPONENTS IN THE TBL WILL BE OBTAINED USING A LASER DOPPLER VELOCIMETER. FINALLY LASER HOLOGRAPHY OR LASER SURFACE SLOPE MEASUREMENTS WILL BE UTILIZED TO CHARACTERIZE THE SURFACE DISPLACEMENT OF THE COMPLIANT LAYER.

IN SUMMARY THE EXPERIMENTAL EFFORT SEEKS TO PROVIDE AN ADEQUATE DATA BASE FOR UNDERSTANDING THE COMPLEXITIES OF COMPLIANT LAYER/FLOW INTERACTIONS.

NEXT SLIDE

THIS SLIDE DESCRIBES THE DIRECTION OF ANALYTICAL EFFORTS BEING CONDUCTED BY CRAIG WAGNER AT NUSC. THE AIM IS TO PROVIDE AN ANALYTICAL FRAMEWORK FOR USE IN SELECTING APPROPRIATE LAYERS AND FOR USE IN DATA INTERPRETATION OF EXPERIMENTAL RESULTS.

INITIAL EFFORTS WERE DIRECTED AT EXTENDING DOWLING'S EARLY WORK BASED ON THE LIGHTHILL ACOUSTIC ANALOGY TO MODEL THE FLUCTUATING PRESSURE OVER A TWO LAYERED VISCOELASTIC MATERIAL. THE SPECIFIC OBJECTIVE WAS TO DEVELOP A MODEL FOR THE FLUCTUATING PRESSURE CAUSED BY THE TBL AT THE SURFACE AND WITHIN A VISCOELASTIC LAYER BACKED BY A STEEL PLATE. A FURTHER OBJECTIVE WAS TO EXTEND THE MODEL TO ACCOMODATE THE CASE OF AN ANISOTROPIC LAYER WITH A STEEL BACKING PLATE. THESE EFFORTS WHICH HAVE BEEN LARGELY ACCOMPLISHED WILL BE DISCUSSED FURTHER.

BEFORE PROCEEDING, HOWEVER, IT SHOULD BE NOTED THAT METHODS ARE ALSO BEING SOUGHT TO EXTEND THE ANALYTICAL MODELING OVER A WIDER RANGE OF WAVENUMBER VALIDITY. SUCH EXTENSIONS ARE NEEDED IF THE COMPLETE PHYSICS OF FLOW/LAYER INTERACTION IS TO BE UNRAVELED OVER THE FULL WAVEVECTOR FREQUENCY DOMAIN. ALSO OF INTEREST IS THE POSSIBILITY OF DEVELOPING A MODEL FOR THE TURBULENCE SOURCE TERMS. CURRENT MODELS OF THE FLUCTUATING PRESSURE ON A COMPLIANT LAYER PROVIDE A WAVENUMBER FREQUENCY SPECTRAL REPRESENTATION NON-DIMENSIONALIZED BY THE TURBULENCE SOURCE TERMS Q_{IJKL}. CONSEQUENTLY ONLY RELATIVE PRESSURE LEVELS CAN CURRENTLY BE OBTAINED.

NEXT SLIDE.

THIS SLIDE SHOWS THE GEOMETRY OF THE INITIAL EXTENSIONS OF DOWLING'S MODEL BY WAGNER TO INCLUDE A TWO LAYERED SURFACE. THIS MODEL ASSUMES A SEMI INFINITE TURBULENT FIELD OVER THE TWO LAYERED STRUCTURE WHICH IS BACKED BY A FLUID AT REST. THE TWO LAYERS MAY HAVE DIFFERENT COMPLEX SHEAR MODULII G' AND G", DIFFERENT COMPLEX ELASTIC MODULII E' AND E", DIFFERENT DENSITIES ρ' AND ρ'' AND DIFFERENT THICKNESSES t' AND t". THE TURBULENT FLUID AND LOWER FLUID MAY HAVE DIFFERENT DENSITY, VISCOSITY AND SOUND SPEED.

THE OBJECTIVE OF THE MODEL IS TO DETERMINE THE WAVENUMBER FREQUENCY SPECTRA OF THE FLUCTUATING WALL PRESSURE AT THE SURFACE OF THE VISCOELASTIC LAYER, WITHIN THE LAYER AND AT THE INTERFACE BETWEEN THE LAYERS.

NOW WE TURN TO SOME OF THE RESULTS FROM THIS MODEL.

NEXT SLIDE.

THIS SLIDE SHOWS THE NON-DIMENSIONAL PRESSURE SEPCTRUM ON THE SURFACE OF A 1 INCH THICK STEEL PLATE AS A FUNCTION OF FREQUENCY AND STREAMWISE WAVENUMBER k_1. IN THIS FIGURE THE FREQUENCY RANGE EXTENDS FROM 100 Hz TO 10 kHz. THE STREAMWISE WAVENUMBER k_1 HAS BEEN NON-DIMENSIONALIZED BY THE ACOUSTIC WAVENUMBER ω/C. THE PRESSURE SPECTRAL DENSITY AMPLITUDE HAS BEEN NON-DIMENSIONALIZED BY FLUID DENSITY ρ, FLOW VELOCITY U, BOUNDARY LAYER THICKNESS H AND THE TURBULENCE SOURCE TERMS Q_{IJKL}.

CLEARLY EVIDENT AT A DIMENSIONLESS WAVENUMBER OF 1, IS THE SINGULARITY AT THE ACOUSTIC WAVENUMBER AS SHOWN BY DOWLING. THE RIDGE OF ENERGY SHOWN COMING IN FROM THE RIGHT OF THE FIGURE CORRESPONDS TO THE FLEXURAL WAVES IN THE PLATE. A TRACE OF ENERGY CAN ALSO BE SEEN AT $k^+=0.3$ WHICH CORRESPONDS TO COMPRESSIONAL WAVES IN THE PLATE.

IF ONE WERE TO CONSIDER A SLICE AT CONSTANT FREQUENCY THE RESULTANT CURVE SHOWING THE NON-DIMENSIONAL SPECTRAL LEVEL AS A FUNCTION OF DIMENSIONLESS WAVENUMBER IS IDENTICAL TO DOWLING'S PUBLISHED RESULTS. THESE DATA HAVE BEEN SHOWN TO CONFIRM THAT OUR EFFORTS ARE IN CONCERT WITH DOWLING'S PUBLISHED RESULTS.

AN INTERESTING SIDELIGHT IS THAT THIS PLOT, WHICH IS TYPICAL, WAS GENERATED ON A CRAY XMP COMPUTER IN 4 MINUTES AT A COST OF ABOUT $100. BY WAY OF CONTRAST A SIMILAR RUN ON A VAX SYSTEM REQUIRES ABOUT 18 HOURS AND A COST OF $3,600.

NEXT SLIDE.

IN THIS SLIDE IS SHOWN THE NON-DIMENSIONAL PRESSURE SPECTRUM ON THE SURFACE OF A VISCOELASTIC LAYER OF 3 INCH THICKNESS MOUNTED ON THE 1 INCH THICK STEEL BACKING PLATE. THE VISCOELASTIC LAYER HAS BEEN CHOSEN TO HAVE A DENSITY EQUAL TO THAT OF WATER, A POISSIN'S RATIO OF 0.5 AND 5% DAMPING. THE FREQUENCY RANGE, DIMENSIONLESS WAVENUMBER RANGE AND AMPLITUDE PARAMETER ARE THE SAME AS ON THE PREVIOUS SLIDE FOR THE BARE STEEL PLATE.

ENERGY AT THE FLEXURAL WAVENUMBER IS STILL EVIDENT COMING IN FROM THE RIGHT OF THE FIGURE TOWARD A VALUE OF $K^+ = 1$ WITH INCREASING FREQUENCY. HOWEVER, IT IS NO LONGER THE CLEAR DISTINCT RIDGE SHOWN FOR THE PLAIN STEEL PLATE. EVIDENCE OF THE SINGULARITIES AT ACOUSTIC AND COMPRESSIVE WAVENUMBERS IS STILL PRESENT BUT ALTERED IN CHARACTER. IN ADDITION, ONE CAN CLEARLY SEE ADDITIONAL SPECTRAL FEATURES INTRODUCED BY THE PRESENCE OF THIS COATING ON THE STEEL PLATE.

NEXT SLIDE.

THE NON-DIMENSIONAL WAVENUMBER FREQUENCY SPECTRUM AT THE INTERFACE BETWEEN THE 3 INCH VISCOELASTIC LAYER AND THE 1 INCH STEEL PLATE IS SHOWN IN THIS FIGURE. INDICATIONS OF THE FLEXURAL WAVES, THE ACOUSTIC SINGULARITY AND COMPRESSIONAL WAVES CAN BE SEEN. HOWEVER, IT IS ALSO NOTED THAT MUCH LESSER EFFECTS ARE EVIDENT IN OTHER WAVENUMBER REGIONS WHERE THE TOP SURFACE SPECTRUM SHOWED SIGNIFICANT FEATURES.

COMPARISON PLOTS OF NON-DIMENSIONAL SPECTRAL LEVELS AT SELECTED FREQUENCIES WHICH ARE NOT SHOWN HERE DUE TO TIME CONSTRAINTS HAVE BEEN MADE FOR THE UNCOATED STEEL PLATE, THE TOP SURFACE OF THE VISCOELASTIC LAYER AND THE INTERFACE BETWEEN THE VISCOELASTIC LAYER AND THE STEEL PLATE. FOR THIS PARTICULAR MATERIAL WHICH HAS COMPRESSIVE AND SHEAR WAVE SPEEDS NOT TOO FAR REMOVED FROM THE ACOUSTIC VELOCITY, IT IS EVIDENT THAT ADDITIONAL SINGULARITIES CAN BE INTRODUCED INTO THE PRESSURE SPECTRUM. SUCH A SURFACE CAN ALSO LEAD TO APPARENT INCREASES IN SPECTRAL LEVELS AT THE HIGHER WAVENUMBERS IN COMPARISON TO LEVELS ON A BARE STEEL PLATE.

SIMILAR CALCULATIONS WHICH ARE NOT SHOWN HERE HAVE BEEN CARRIED OUT FOR THE FLUCTUATING STREAMWISE SHEAR STRESS SPECTRA.

THE NEXT STEP IS TO EXERCISE THE MODEL ON SPECIFIC CANDIDATE SURFACES UNDER CONSIDERATION FOR EXPERIMENTAL INVESTIGATION TO AID IN SELECTION OF THE MOST PROMISING MATERIALS.

NEXT SLIDE.

THIS SLIDE ILLUSTRATES THE GEOMETRY OF THE MODEL AS CURRENTLY EXTENDED. IN THIS CASE THE TURBULENCE ONLY OCCUPIES A FINITE REGION WITHIN THE BOUNDARY LAYER. A MEAN VELOCITY PROFILE IS INCLUDED WITHIN THE BOUNDARY LAYER. AND THE MAJOR DEVELOPMENT IS PROVISION FOR ANISOTROPY IN THE LAYER ADJACENT TO THE FLOW. THE SPECIFIC CASE WHICH HAS BEEN DEVELOPED ALLOWS FOR ANISOTROPY IN THE VERTICAL DIRECTION WITH ISOTROPY PREVAILING IN THE TRANSVERSE DIRECTIONS. CALCULATIONS HAVE NOT YET BEEN MADE FOR THIS CASE.

ONE FURTHER GENERALIZATION FOR THIS MODEL IS PLANNED TO ACCOMODATE AN ANISOTROPIC LAYER WHEREIN THE PROPERTIES IN THE VERTICAL AND TWO TRANSVERSE DIRECTIONS ARE ALL DIFFERENT. IT IS NOT CURRENTLY PLANNED TO PURSUE EXTENSION TO THE COMPLETELY GENERAL ANISOTROPIC LAYER CASE.

NEXT SLIDE.

WE NOW TURN BRIEFLY TO THE THIRD ASPECT OF THE NUSC PROGRAM ON COMPLIANT SURFACES. THIS APPROACH UTILIZES STATE-OF-THE-ART NUMERICAL METHODS FOR TURBULENCE MODELING COUPLED WITH THE ADJACENT ELASTIC LAYER PROBLEM. THIS WORK IS UNDER THE DIRECTION OF JACK KALINOWSKI AT NUSC WITH MURRAY WACHMAN OF THE UNIVERSITY OF CONNECTICUT.

THE PRESENT STATUS IS THAT A COMPUTATIONAL STRATEGY HAS BEEN DEVISED TO INCLUDE WEAK FLUID INCOMPRESSIBILITY (ACOUSTIC EFFECTS) AND A NONLINEAR FLUID/STRUCTURE BOUNDARY CONDITION EMPLOYING AN ARBITRARY EULERIAN-LAGRANGIAN COORDINATE TRANSFORMATION. THE COORDINATE TRANSFORMATION WAS SPECIFICALLY DEVISED TO HANDLE THE MOVING SURFACE WHICH IF VIEWED IN THE USUAL STATIONARY OBSERVER EULERIAN SYSTEM WOULD BE SEEN TO MOVE ALTERNATELY BACK AND FORTH WITH RESPECT TO COMPUTATIONAL GRID POINTS LOCATED AT THE MEAN PLATE BOUNDARY. WITHOUT THIS TRANSFORMATION FLUID COMPUTATIONAL GRID POINTS NEAR THE LAYER WOULD ALTERNATELY BE LOCATED WITHIN THE FLUID AND WITHIN THE LAYER, AS THE LAYER MOVES UNDER THE INFLUENCE OF FLOW. COMPUTER CODING OF THE FULL NAVIER STOKES EQUATIONS FOR THE CASE OF FLOW OVER A DAMPED ORTHOTROPIC PLATE IS COMPLETED BUT NOT YET VALIDATED. SUBSEQUENT EXTENSIONS WILL INCLUDE A FINITE ELEMENT REPRESENTATION OF A GENERAL VISCOELASTIC STRUCTURE.

NEXT SLIDE.

THIS SLIDE ILLUSTRATES RESULTS OBTAINED FOR NUSC BY MOIN OF NASA-AMES FOR FLOW OVER AN ELASTIC PLATE. THE GEOMETRY OF THE MODEL IS SHOWN IN THE INSET AT THE RIGHT. THE SURFACE DEFORMATION OF THE ELASTIC PLATE AND THE CORRESPONDING SPATIAL PRESSURE FIELD ARE SHOWN IN THE UPPER AND LOWER FIGURES RESPECTIVELY. WHILE THESE RESULTS ARE IMPRESSIVE IN THE DETAILS OF THE SURFACE DEFORMATION AND OF THE SPATIAL PRESSURE FIELD, THE CALCULATIONS ARE BASED ON THE USE OF AN EULERIAN SYSTEM OF GRID POINTS AND A LINEARIZED BOUNDARY CONDITION USING A ONE TERM TAYLOR EXPANSION.

WITH NO PRETENSE OF BELITTLING MOIN'S EFFORTS CONDUCTED IN CONJUNCTION WITH THE ONR DRAG REDUCTION PROGRAM, THE NUSC EFFORT IS DIRECTED TO MORE COMPLETELY ACCOUNT FOR THE FLUID/LAYER BOUNDARY CONDITION. AS A MATTER OF RECORD NUSC PERSONEL ARE WORKING CLOSELY WITH NASA-AMES IN THIS AREA.

NEXT SLIDE.

THIS SLIDE LISTS THE OUTPUT QUANTITIES THAT WILL BE AVAILABLE FROM THE NUMERICAL SIMULATIONS. THEY INCLUDE A MOVIE FILM REPRODUCTION OF THE NUMERICAL CALCULATIONS THAT CLEARLY ILLUSTRATES THE FLOW CHARACTERISTICS AS THEY EVOLVE, WAVENUMBER FREQUENCY SPECTRA OF RESPONSE QUANTITIES, TWO POINT CORRELATION FUNCTIONS, COMPARISON OF QUANTITIES FOR FLOWS OVER A RIGID WALL AND OVER A COMPLIANT LAYER, QUANTITATIVE EVALUATION OF THE TURBULENCE SOURCE TERMS APPEARING IN THE LIGHTHILL ACOUSTIC ANALOGY AND VELOCITY PROFILES.

SLIDE OFF.

IN CONCLUSION, WE HAVE BRIEFLY SUMMARIZED THE NAVAL UNDERWATER SYSTEMS CENTER INDEPENDENT RESEARCH AND EXPLORATORY DEVELOPMENT PROGRAM ON COMPLIANT LAYERS. OUR THREE FACETED APPROACH USING STATE-OF-THE-ART EXPERIMENTS, ANALYTICS AND NUMERICS IS BELIEVED CAPABLE OF PROVIDING INSIGHT INTO THE COMPLEXITIES OF THE INTERACTIONS OF A COMPLIANT LAYER WITH A TURBULENT FLOW. ONCE AGAIN WE WISH TO ACKNOWLEDGE THE EFFORTS OF CRAIG WAGNER IN ANALYTICS AND JACK KALINOWSKI IN THE NUMERICAL MODELING.

(U) Hydrodynamic Noise and Surface Compliance

Naval Underwater Systems Center
Program Overview

Henry P. Bakewell, Jr.
William A. von Winkle

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(U) Investigations of Hydrodynamic Noise on Compliant Surfaces

OBJECTIVE

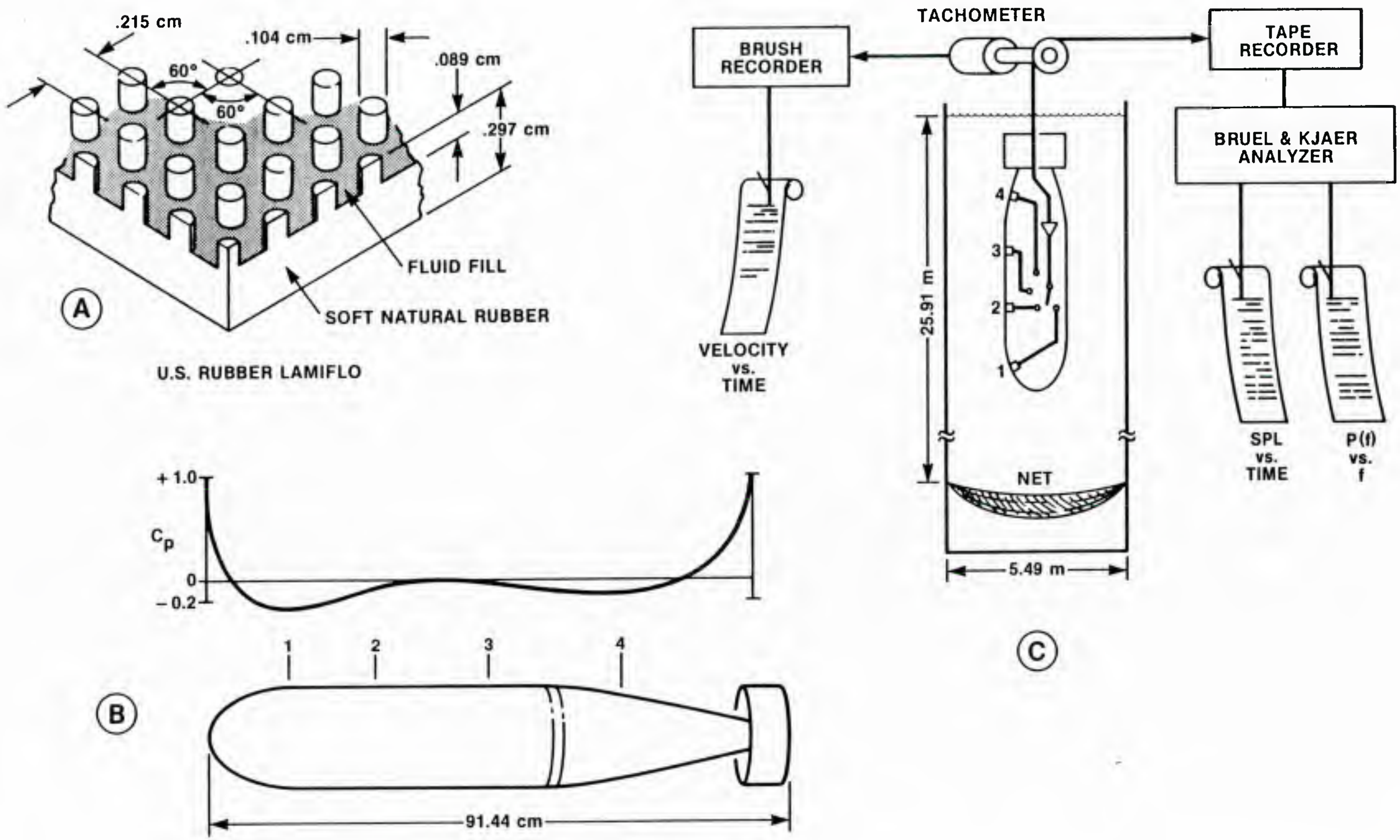
- CHARACTERIZE THE INTERACTION BETWEEN A TURBULENT BOUNDARY LAYER FLOW AND COMPLIANT SURFACES FOR CONTROL AND REDUCTION OF FLOW NOISE

MOTIVATION

- SIGNIFICANT REDUCTION OF TBL WALL PRESSURE FLUCTUATIONS OBSERVED IN 1960 EXPERIMENT (25 dB AT MID FREQUENCIES)

BPH32-040485A

(U) Compliant Layer Experiment



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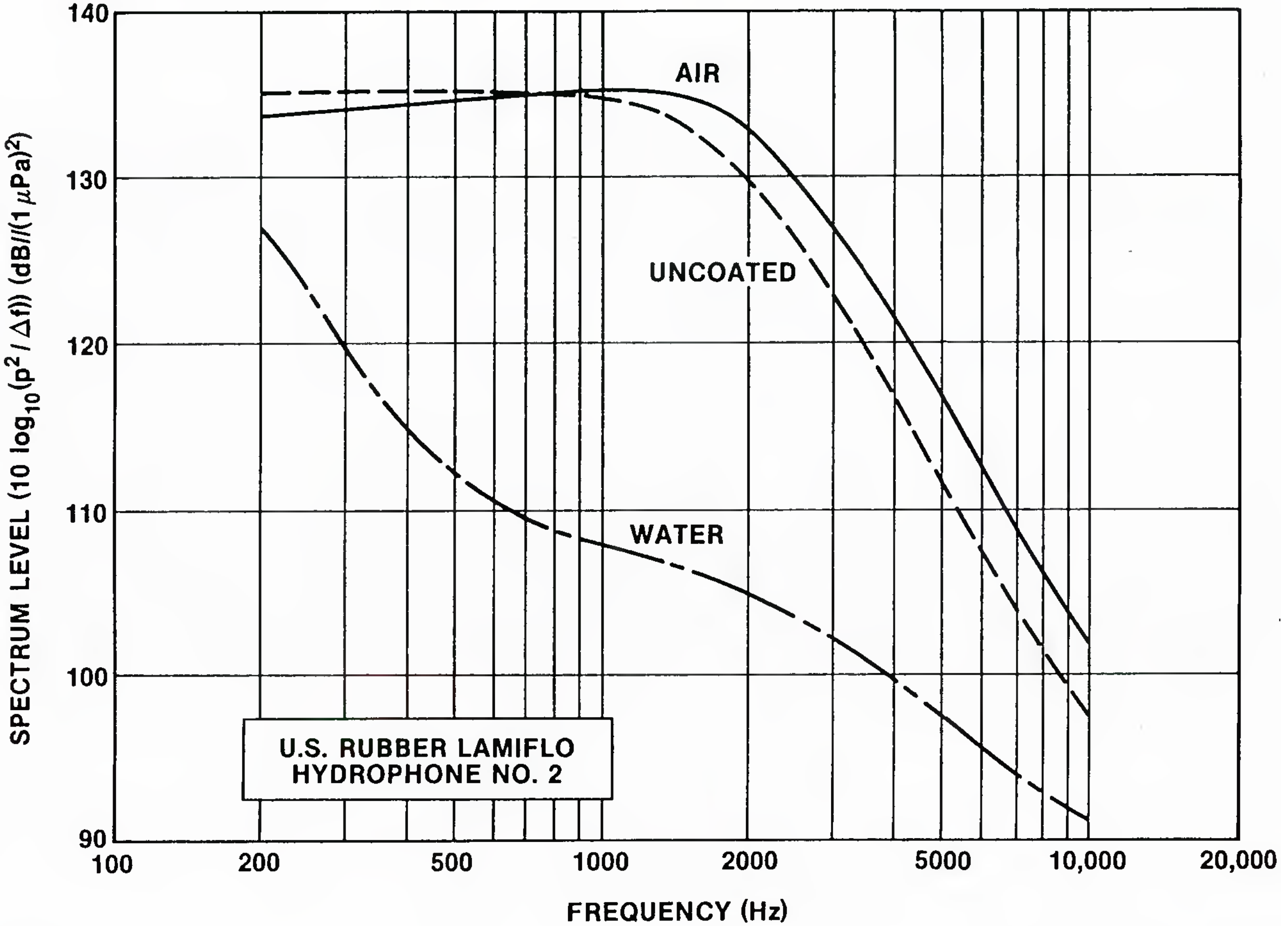
(U) Effect of Compliant Layer on TBL Wall Pressure



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(U) Compliant Surface Noise Reduction Past and Present Efforts

- 1960 NAVAL UNDERWATER SOUND LABORATORY EXPERIMENT
- FOLLOW-ON NAVAL UNDERWATER SOUND LABORATORY EXPERIMENT (EARLY 60s)
- SOVIET ACTIVITIES (70s) - PATENTS AND LIMITED PUBLICATIONS
- UNITED KINGDOM ACTIVITIES - ANALYTICAL STUDIES
- CURRENT NAVAL UNDERWATER SYSTEMS CENTER IR/IED PROGRAM
  - EXPERIMENTAL STUDY IN NUSC/NL WATER TUNNEL UNDER CONTROLLED FLOW/TEMPERATURE CONDITIONS
  - SUPPORTING ANALYTICAL AND NUMERICAL STUDIES TO PROVIDE PREDICTIVE GUIDANCE IN MATERIAL PROPERTY SELECTION TO AID EXPERIMENTAL DATA INTERPRETATION AND TO ENABLE QUANTITATIVE PREDICTIONS

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(U) Compliant Layer Noise Reduction

APPROACH (EXPERIMENTAL)

- DESIGN AND CONDUCT COMPLIANT SURFACE EXPERIMENTS UNDER CONSTANT TEMPERATURE AND VELOCITY CONDITIONS IN NUSC/NL WATER TUNNEL TO MEASURE:
  - TBL FLUCTUATING WALL PRESSURE STATISTICS
  - TBL NOISE TRANSMISSION IN LAYER
  - WALL SHEAR STRESS CHARACTERISTICS
  - WALL LAYER FLUCTUATING VELOCITY CHARACTERISTICS
  - SURFACE DISPLACEMENT

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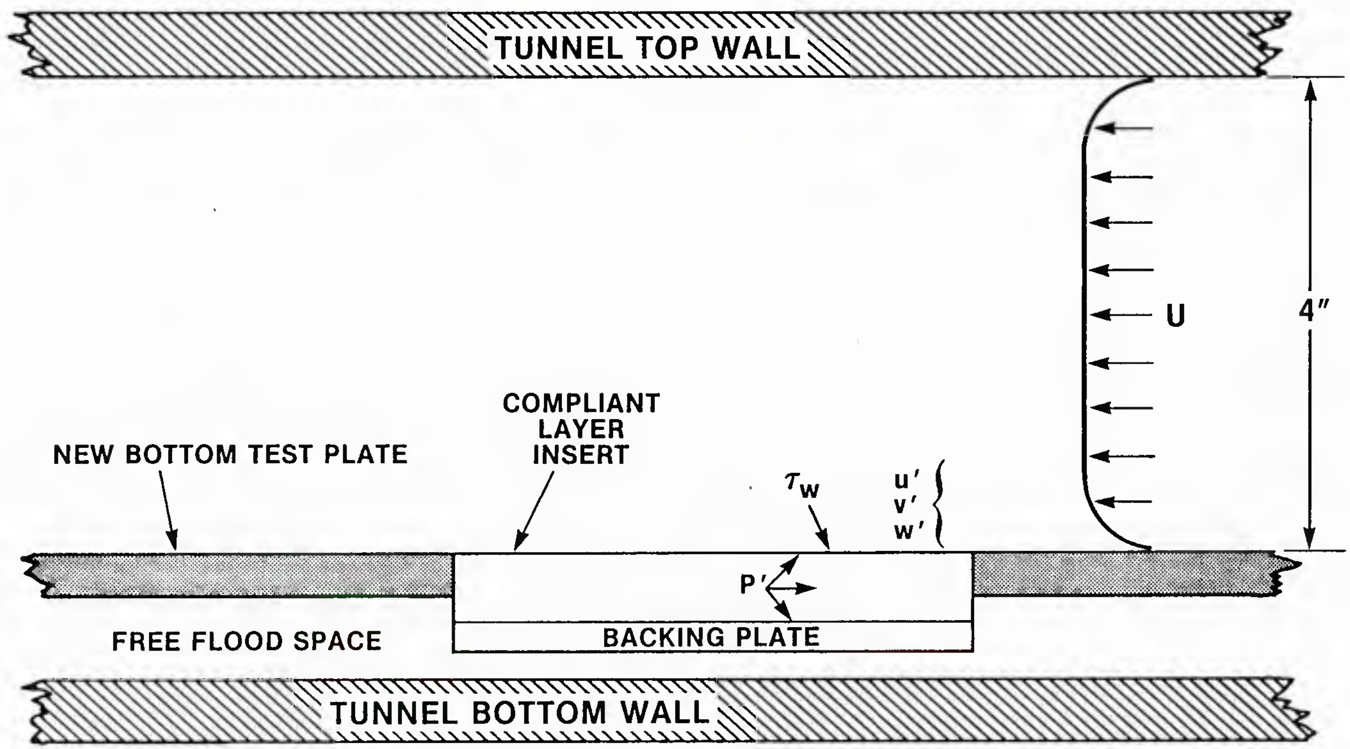
(U) Sketch of Experimental Setup



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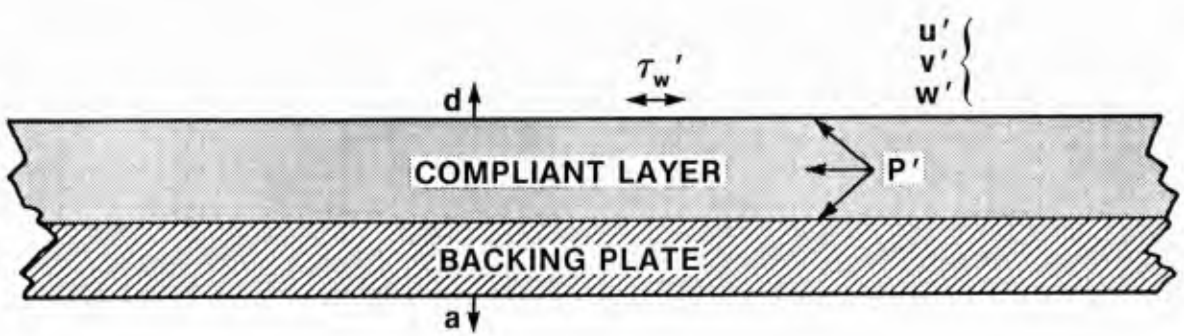
(U) Experimental Measurements

$P'_{SURFACE}$	- CERAMIC SENSORS IN PROBE MOUNT BULK MODE EMBEDDED SENSORS	WAVE VECTOR FILTER ARRAYS
$P'_{IN\ LAYER}$	- CERAMIC CYLINDERS BULK MODE SENSORS	
P'_{PLATE}	- FLUSH MOUNT CERAMICS	
a_{PLATE}	- ACCELEROMETERS	
$\tau_w{}'_{TBL}$	- HOT FILM PROBES	
$\tau_w{}'_{TBL} + \tau_{SURFACE}$	- POLYMER FILM SENSORS	
u', v', w'	- LDV	
d	- LASER HOLOGRAPHY - LASER SLOPE MEASUREMENTS	



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TM No. 851080

(U) Compliant Layer Noise Reduction Approach (Analytical)

- ANALYTICAL MODELS FOR USE IN SELECTING CANDIDATE LAYER MATERIAL PROPERTIES AND TO ENABLE INTERPRETIVE ANALYSIS OF EXPERIMENTS
  - EXTENSIONS OF DOWLING-FFOWCS WILLIAMS WALL PRESSURE MODEL TO INCLUDE TWO LAYERED ISOTROPIC VISCOELASTIC MATERIAL
  - EXTENSIONS OF ISOTROPIC MODEL TO INCLUDE GENERAL ANISOTROPIC LAYER ABOVE AN ELASTIC LAYER (COMPLIANT SURFACE ON A BACKING PLATE)
  - INVESTIGATE HIGHER WAVENUMBER APPLICABILITY OF MODEL THROUGH COMPARISON WITH EXPERIMENTAL DATA AND OTHER ANALYTICAL MODELS WHICH INCLUDE CONVECTIVE WAVENUMBER REGION
  - DEVELOP A MODEL FOR UNKNOWN Qijkl TURBULENT SOURCE TERMS TO GIVE ABSOLUTE PRESSURE MAGNITUDE - MODEL CURRENTLY GIVES RELATIVE WALL PRESSURE

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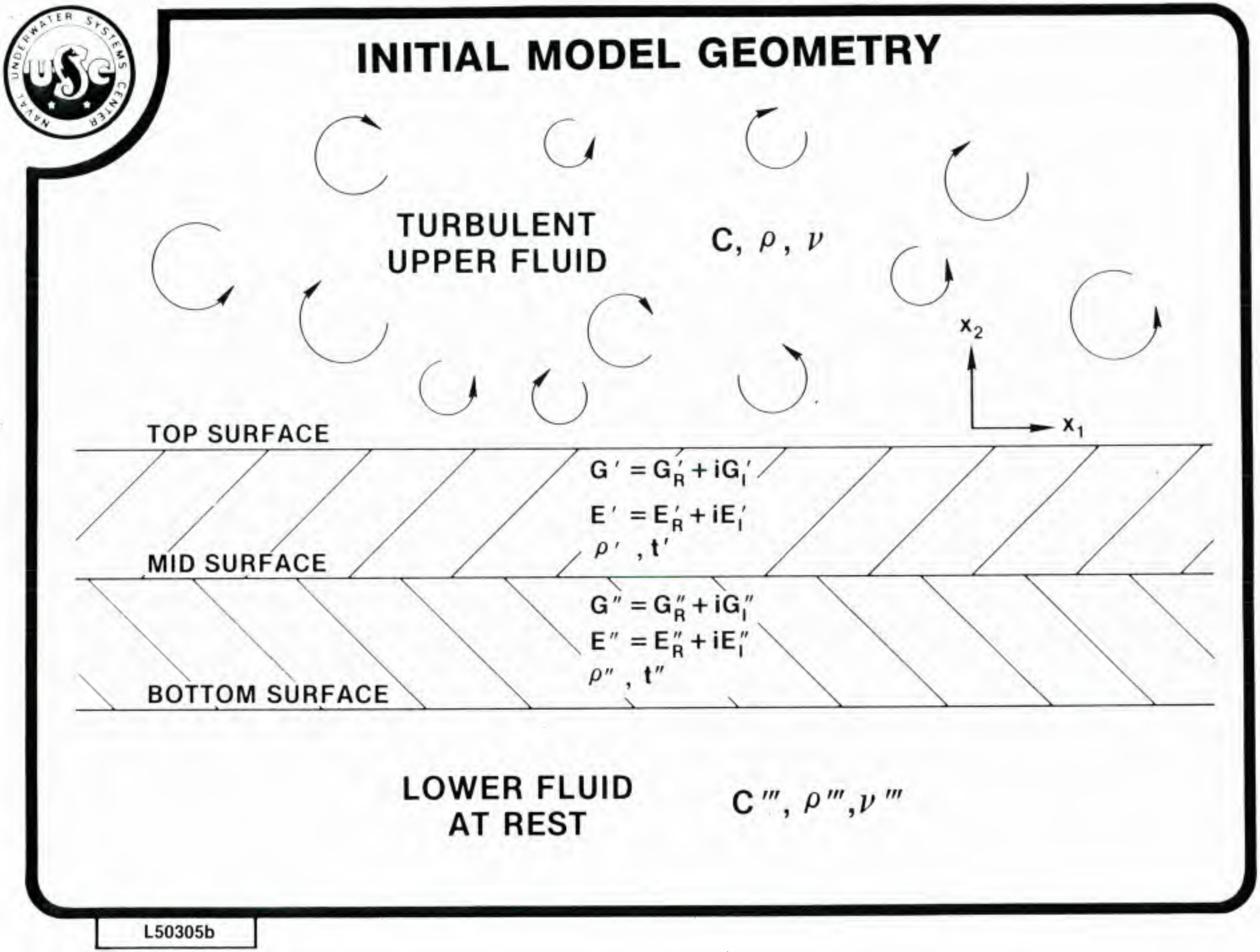
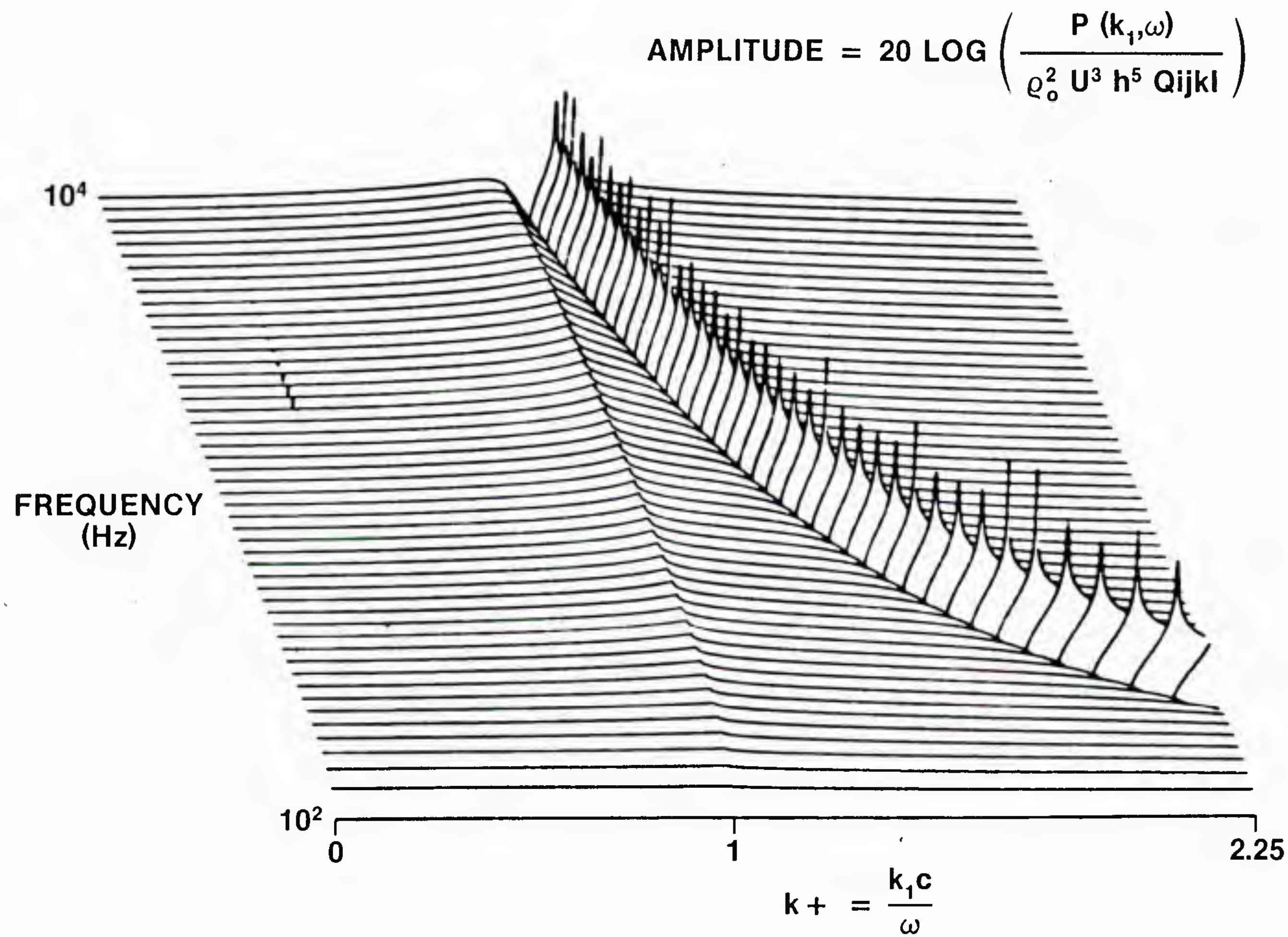

INITIAL MODEL GEOMETRY
TURBULENT UPPER FLUID
C, ρ, ν
x_2
x_1
TOP SURFACE
$G' = G'_R + iG'_I$
$E' = E'_R + iE'_I$
ρ' , t'
MID SURFACE
$G'' = G''_R + iG''_I$
$E'' = E''_R + iE''_I$
ρ'' , t''
BOTTOM SURFACE
LOWER FLUID AT REST
C''', ρ''', ν'''
L50305b

(U) Nondimensional Pressure Spectrum on Surface of 1″ Thick Steel Plate



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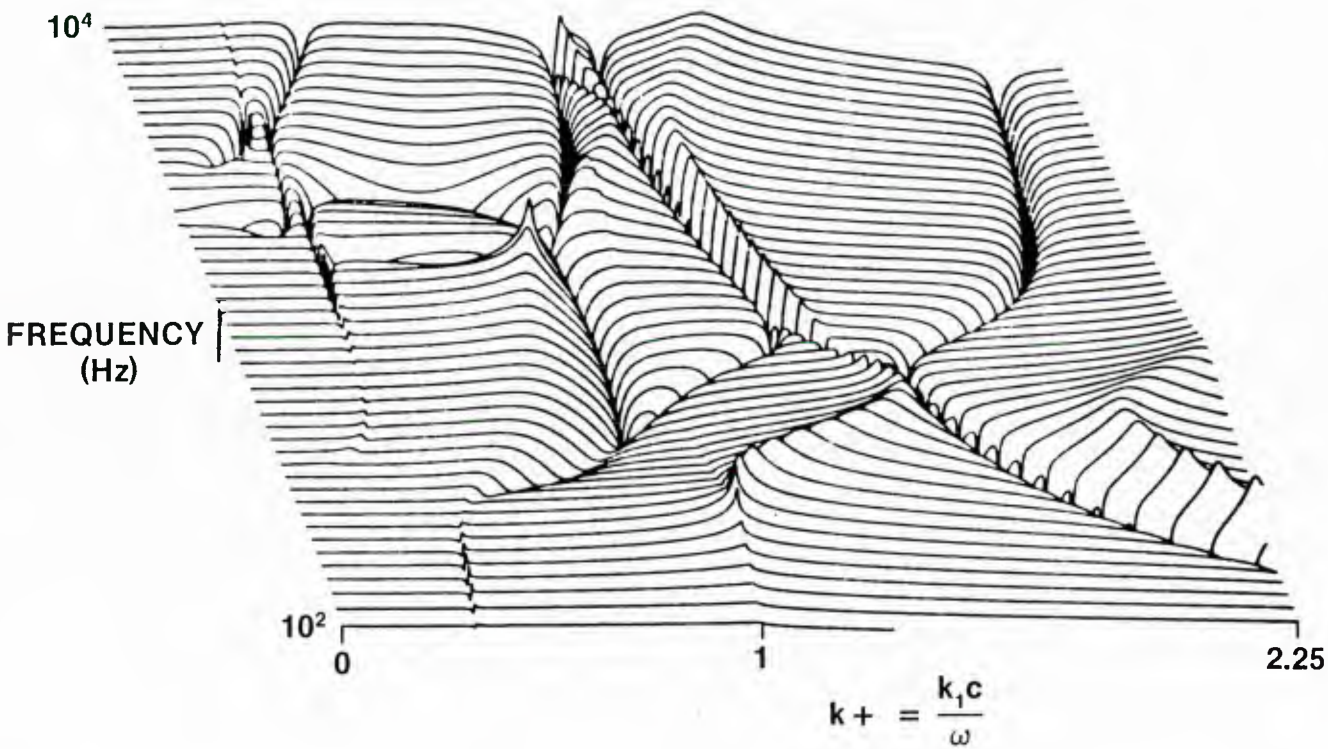
(U) Nondimensional Pressure Spectrum on Viscoelastic Surface Mounted on 1″ Steel Plate

3″ VISCOELASTIC LAYER PROPERTIES

$E = 252{,}000$ psi $\quad \nu = 0.5 \quad$ 5% DAMPING $\quad$ AMPLITUDE $= 20 \text{ LOG} \left(\dfrac{P\,(k_1,\omega)}{\varrho_o^2\, U^3\, h^5\, Q_{ijkl}} \right)$

$G = 90{,}000$ psi $\quad \varrho = \varrho_{WATER}$



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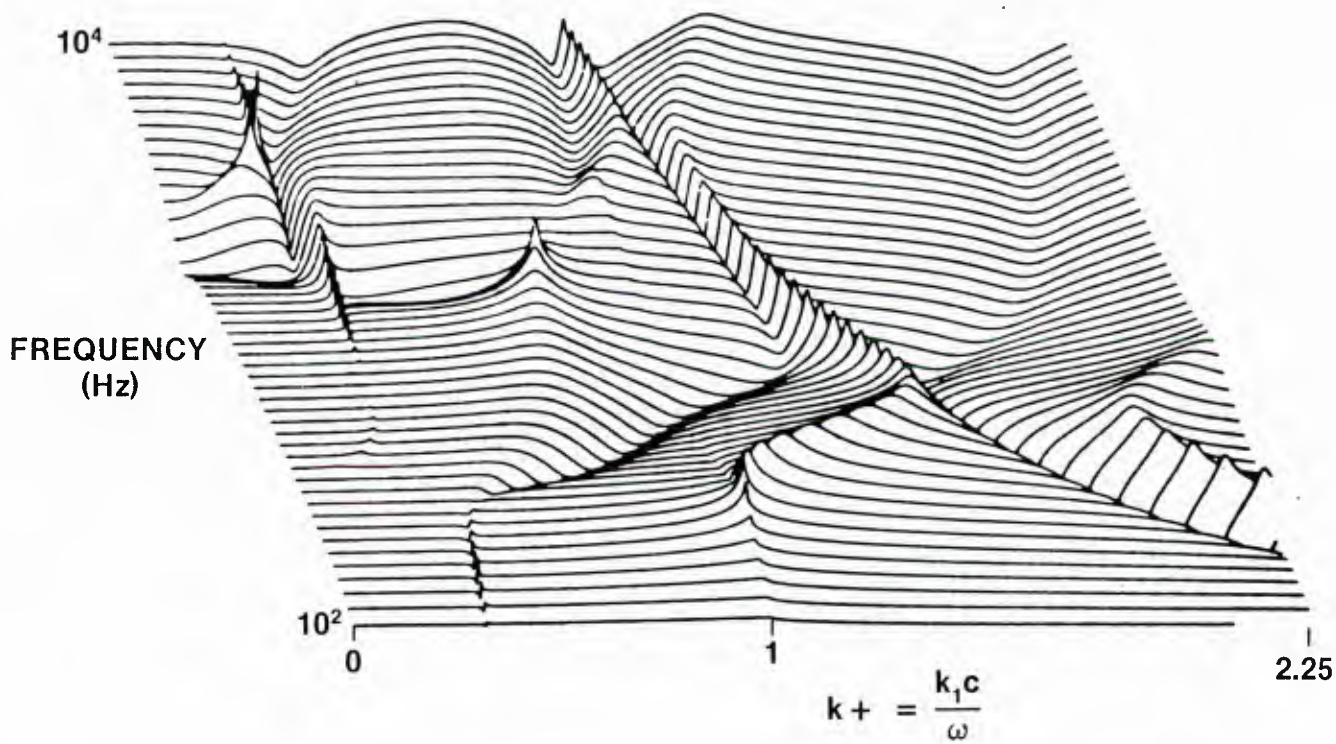
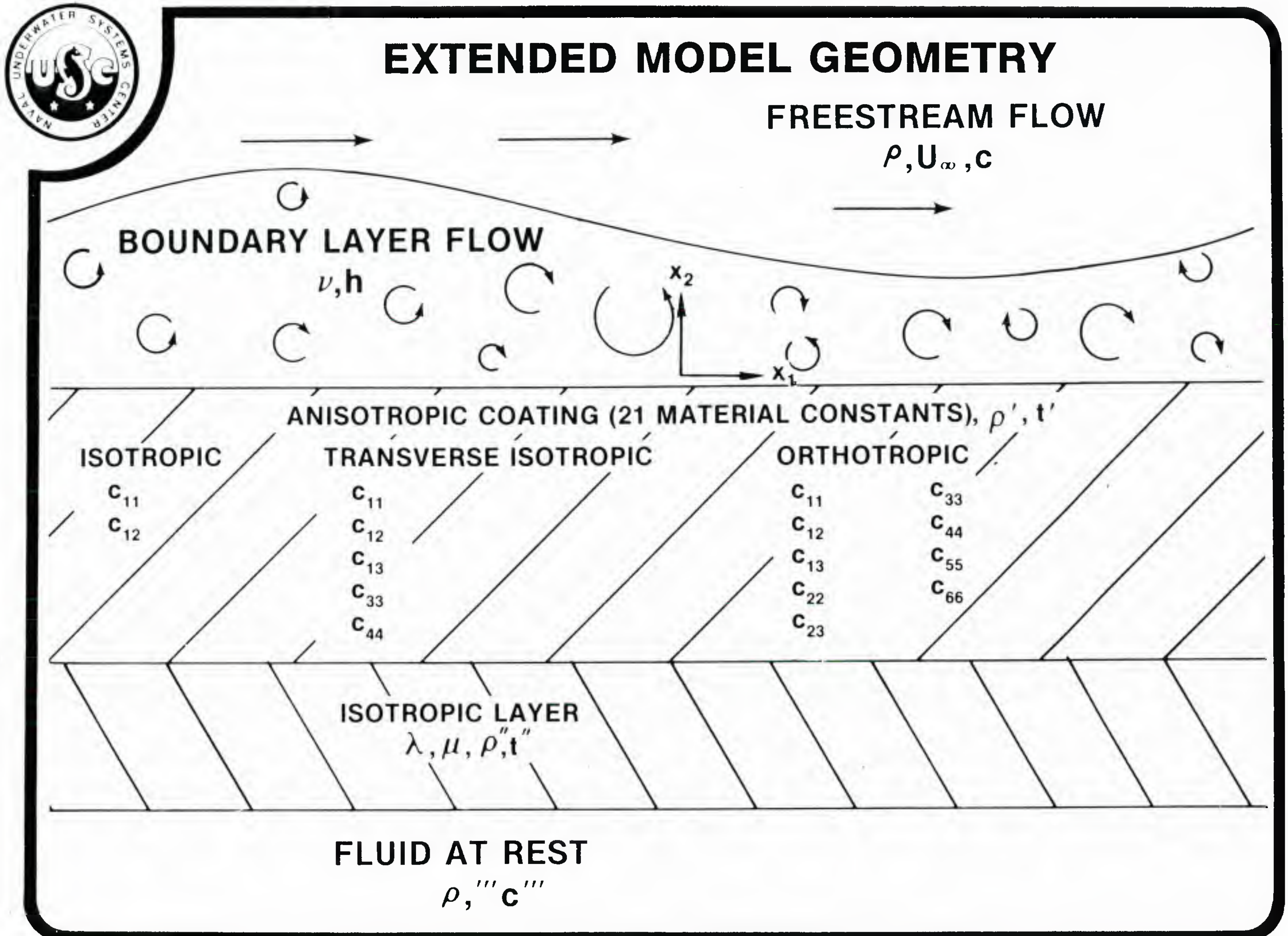
(U) Nondimensional Pressure Spectrum at Bottom of Viscoelastic Layer Mounted on 1″ Steel Plate

3″ VISCOELASTIC LAYER PROPERTIES

$E = 252{,}000$ psi $\nu = 0.5$ 5% DAMPING AMPLITUDE $= 20 \text{ LOG} \left(\dfrac{P\,(k_1,\omega)}{\varrho_o^2\, U^3\, h^5\, \text{Qijkl}} \right)$

$G = 90{,}000$ psi $\varrho = \varrho_{WATER}$





EXTENDED MODEL GEOMETRY
FREESTREAM FLOW
ρ, U_∞, c
BOUNDARY LAYER FLOW
ν, h
x_2
x_1
ANISOTROPIC COATING (21 MATERIAL CONSTANTS), ρ', t'
ISOTROPIC
c_{11}
c_{12}
TRANSVERSE ISOTROPIC
c_{11}
c_{12}
c_{13}
c_{33}
c_{44}
ORTHOTROPIC
c_{11}
c_{12}
c_{13}
c_{22}
c_{23}
c_{33}
c_{44}
c_{55}
c_{66}
ISOTROPIC LAYER
$\lambda, \mu, \rho'', t''$
FLUID AT REST
ρ''', c'''

L50305b

COMPLIANT LAYER NOISE REDUCTION

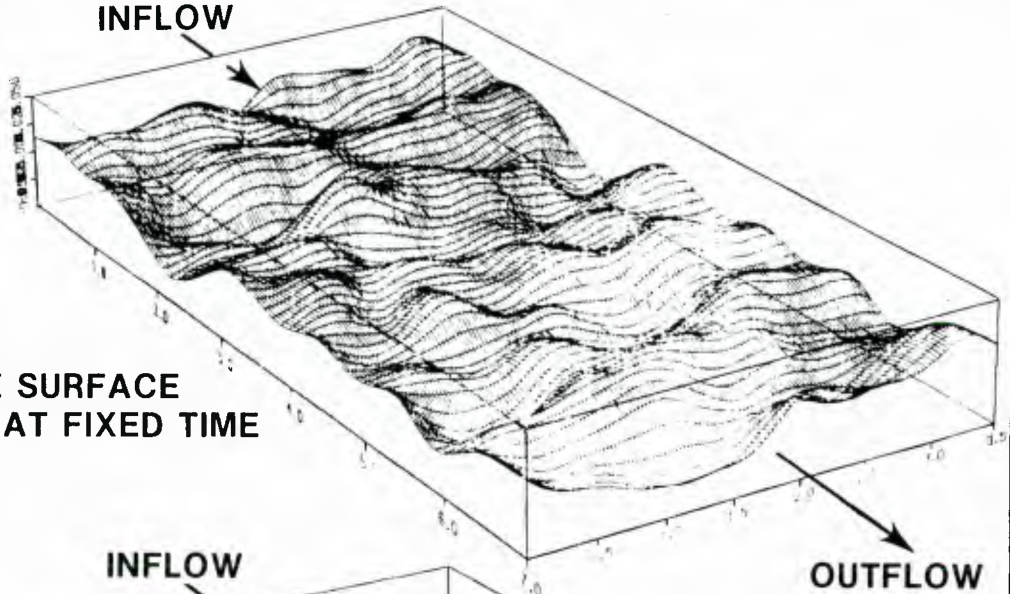
APPROACH (NUMERICAL)

- DEVELOP A NUMERICAL CAPABILITY TO CALCULATE THE FLUCTUATING PRESSURE FIELD AT THE FLUID/LAYER INTERFACE IN TURBULENT FLOW.

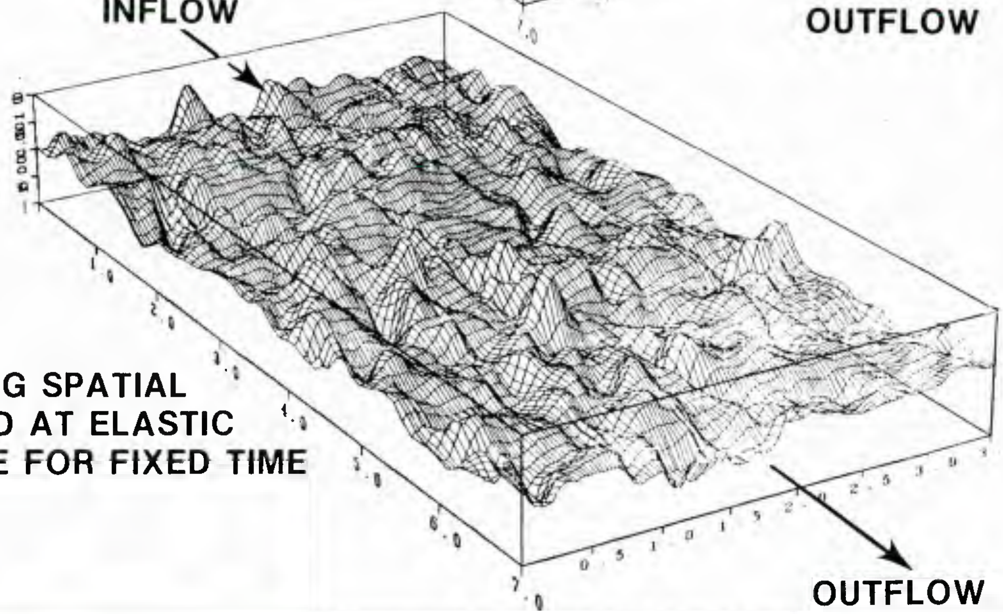
- SOLVE NUMERICALLY THE NAVIER-STOKES FLUID EQUATIONS AND THE VISCOELASTIC LAYER EQUATIONS USING PSEUDO-SPECTRAL METHODS FOR THE FLUID AND FINITE ELEMENT OR ANALYTICAL METHODS FOR THE VISCOELASTIC LAYER.

L50346c

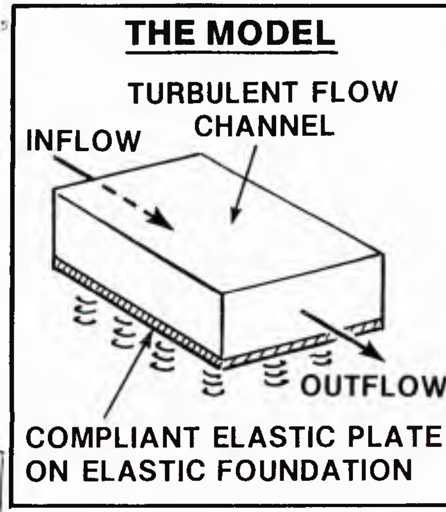
TRANSIENT LARGE EDDY SIMULATION TURBULENT FLOW FIELD COMPUTATION (PERFORMED ON NASA-AMES CRAY COMPUTER BY MOIN)



ELASTIC PLATE SURFACE
DEFORMATION AT FIXED TIME
T = 400



CORRESPONDING SPATIAL
PRESSURE FIELD AT ELASTIC
PLATE SURFACE FOR FIXED TIME
T = 400



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POST PROCESSING OUTPUT GIVES:

- FLOW VISUALIZATION (INTERACTION OF SURFACE MOTION AND BURSTING VIA MOVIE)
- WAVENUMBER-FREQUENCY SPECTRA OF DESIRED RESPONSE QUANTITIES SUCH AS WALL PRESSURE, VORTICITY, WALL SHEAR STRESS
- X – Z PLANE TWO POINT CORRELATION FUNCTIONS ON SELECTED RESPONSE QUANTITIES
- RIGID vs COMPLIANT WALL SPECTRA COMPARISONS
- Q_{ijkl} TURBULENT SOURCE TERMS (NEEDED FOR QUANTITATIVE PREDICTION USING THE ACOUSTIC ANALOGY)
- VELOCITY PROFILES

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HYDRODYNAMIC NOISE AND SURFACE COMPLIANCE-AN OVERVIEW OF THE NAVAL UNDERWATER SYSTEMS CENTER IR/IED PROGRAM
Dr. Henry P. Bakewell, Jr.
Dr. William A. Von Winkle, Associate Technical for Research and Technology
TM No. 851080
15 May 1985
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